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ABSTRACT

We introduce a novel, time delay-based, transmit-receive mode, remotely located, optical control system for wide instantaneous bandwidth phased arrays. Time delays are achieved using a cascade of free-space and fiber-based optical delay lines using bulk imaging optics for low complexity, two dimensional, free-space optical interconnects. High channel isolation, low insertion loss optical switching between delayed and undelayed paths is based on polarization switching using the low cost nematic liquid crystal arrays and polarizing beam splitters. The system allows for noise reduction via spatial and polarization filtering. A dual-channel time-multiplexed system arrangement is used to implement the fast (e.g., 200 beams/s) radar scan rates using the several millisecond response time nematic liquid crystals.

2. INTRODUCTION

Time delay-based control is required for phased array antennas that are large in size and need wide instantaneous bandwidths for high resolution processing. Today, various optical methods are being investigated to generate transmit-receive mode programmable time delays for next generation wideband phased arrays [1-6], including a transmit-only mode two dimensional (2-D) ferroelectric liquid crystal based architecture [7]. Keys to the success of any such time delay control system are in addressing issues such as increasing channel/ switch isolation, decreasing microwave/optical interconnection complexity, minimizing rf-to-rf insertion loss, improving signal linearity and dynamic range, and minimizing the cost of a time delay unit per antenna element. In this paper, we introduce an optical control system that has potential for addressing these issues via novel system design and the low cost, high performance, commercially available nematic liquid crystal (NLC) display technology. Earlier, we have shown how the high performance, low cost, NLC display technology can be used to form a compact, light weight, electrooptic control system for phase-based phased array antennas [8-9].

The proposed innovative high performance optical time delay control system will be required for next generation wide instantaneous bandwidth, large aperture, high resolution phased array radars. The optical system is based on a 2-D, dual channel, K-bit switched digital delay line structure using the mature NLC flat-panel display technology for implementing the polarization-based optical switching operation [10-12]. The unique features of the NLC display technology coupled with the use of free-space interconnects via bulk optics provides the necessary design platform for forming a high performance, low optical and microwave interconnection complexity, 2-D, optical control system that is ideally suited for large phased array radars with > 1024 independent time-delayed channels. The optical system performs both the transmit and receive operations, with the received signal set summation operation performed by a single spherical lens. This eliminates the complex wideband microwave combiner network required in other optical/microwave phased array control techniques. In addition, the large transmit-mode wideband power splitter network can be eliminated if a single high power laser source is modulated by the transmit signal. This reduction/elimination in microwave splitter/combiner networks can greatly reduce system size, weight, and cost. Time delay is introduced through a cascade of 2-D optical time delay units based on polarizing beamsplitters and free-space and/or fiber-based optical beam propagation. Microwave signal optical modulation and detection is achieved by high speed semiconductor lasers (direct modulation) and photodetectors, respectively. External microwave signal optical modulation via integrated electrooptic modulators can also be used for the system. Because the system is based on optical intensity modulation, and the optical beamformer is remotely located with respect to the antenna array, the optical system can be made robust and insensitive to mechanical vibrations via appropriate packaging, thus not requiring an integrated-optic planar design. The two independent optical system channels are operated in a time-multiplexed fashion to provide the high (e.g., 200 beams/s) antenna scan rates using the milliseconds response time NLCs [8-9]. This approach is also described in references 8 and 9 for a phase-based optoelectronic NLC-based phased array antenna controller.

2. THE OPTICAL TIME DELAY CONTROL SYSTEM

Fig.1 shows a simple three dimensional view of the typical optical time delay architecture to be used for controlling wideband phased arrays. Fig.2 shows the detailed top view of the novel NLC-based time delay-based optical control system. The microwave signal from an oscillator passes through a transmit/receive switch T/R1 to a microwave splitter network that provides all the signals for intensity modulating a two dimensional (2-D) laser diode array. A single high power laser source could be substituted for the laser diode array. Linearly polarized light (e.g., s or horizontally polarized) from the laser diode array is collimated by a 2-D lenslet array LA1, and the collimated colinear beams pass through a high extinction ratio polarizer P. Using the spherical lens pair S1 and S2, light is imaged with demagnification onto a high speed electro-optic switch EOS1, that can be a Pockels cell or a single pixel ferroelectric liquid crystal cell with switching times of a few tens of nanoseconds to a few microseconds, respectively. In its off state, EOS1 does not effect the polarization of the linearly polarized incident light, while, in the on state, EOS1 rotates the incident linear polarization by 90°. After EOS1, light is imaged with magnification onto NLC SLM1 (SLM: spatial light modulator). Before SLM1, light passes through a polarizing beam splitter PBS1 that either allows the incident light to flow straight through PBS1 thus entering channel 1 (Ch 1), or deflects the light by 90° into a total internal reflecting corner prism that redirects the light into channel 2 (Ch 2) of the system. The two channels are operated in a time multiplexed fashion to provide the desired high (e.g., 200 beams/s) radar scan rates using slow response NLC SLMs. Keys to this two channel approach include the several millisecond (e.g., 5 ms) dwell time of fast beam scanning state-of-the-art radars, and the a priori or deterministic nature of radar beam scanning.

Polarizers P are positioned before NLC SLM1 to improve desired beam polarization extinction ratio. For the transmit mode, EOS1 determines whether Ch1 or Ch2 is the active channel in the system, and directs the light through that active channel. NLC SLM1 is a 2-D pixelated array of NLCs (either twisted or parallel-rub birefringent mode NLCs can be used) that act as programmable half-wave plates. The linearly polarized light passing through an NLC pixel can have its polarization rotated by 90°, or in its alternate state, allow the linearly polarized incident light to pass without perturbing the polarization. This effect is used in commercial NLC displays to amplitude modulate the light when the display is placed between parallel or crossed polarizers. Thus, depending on the NLC-SLM1 pixel control settings, the incident light beams either have their polarizations rotated by 90°, or have unaltered polarizations. If a light beam incident on PBS3 is s-polarized, the beam passes through PBS3 into the undelayed path of the system. If the light beam incident on PBS3 is p or vertically polarized, the beam is deflected by 90° by PBS3, and travels into the delayed path of the system.

Fig.3 and Fig.4 show typical time delay units that are arranged in a serial, cascade fashion between PBS3 and PBS4 to form an K-bit switchable optical delay line. Fig.3 shows a free-space delay unit with a free-space delay of length 2L. Fig.4 shows a fiber based delay unit appropriate for long delays. Note that imaging lenses are appropriately positioned to minimize beam spreading from one NLC SLM plane to the next NLC SLM plane. In the fiber delay unit, imaging optics is used to image SLM plane I1 to plane I3 for appropriate coupling into the fibers. Similarly, plane I4 is imaged to the SLM plane I2. The NLC SLMs determine whether a beam passes through the undelayed path, or is deflected into the delayed path. After a beam has acquired its appropriate time delay while passing through the required delay units in the system, it is directed by PBS4 towards NLC SLMN. When using Ch1, NLC SLMN is programmed such that all beams after SLMN are s-polarized, and thus pass through PBSN towards the output port of the system. When using Ch2, NLC SLMN is programmed such that all beams after SLMN are p-polarized, and thus are deflected by 90° by PBSN towards the output port of the system. In either case, after PBSN, the spherical lens pair S5 and S6 are used to image with demagnification, the NLC SLMN plane onto the electro-optic switch EOS3 plane. Like EOS1, EOS3 is a high speed 90° polarization rotator. In the transmit mode, EOS3 is programmed such that the light output from EOS3 is always s-polarized. In this way, light after imaging with magnification (using lenses S6 and S5) passes through PBS towards the system output port. The collimated, time delayed, N X M optical beams that are present at the output port are directed using lenslet array LA3, into an N X M fiber array. This fiber array carrys the N X M time delayed, microwave signal modulated, optical beams to the remote T/R modules. Note that the NLC SLMs have two sets of N X M pixels corresponding to independent channels Ch1 and Ch2. Thus, each NLC SLM has a total of 2N X M pixels. Also note that single spherical lenses can be used in the time delay units to reduce the number of optical components as shown in Fig.5, although this would require larger aperture lenses. In addition, with single spherical lenses, Ch1 and Ch2 get spatially inverted after each delay unit, and thus the system has to be operated accordingly.

Fig.6 shows a typical system scenario and T/R module appropriate for the system in Fig.2. The microwave phase shifter in the module can be used to provide phase-based steering at the sub-array level, in addition, also providing system phase calibration capability. The attenuators are used to correct for amplitude errors across the array, both on transmit and receive modes. The received signals, after appropriate amplification, are used to modulate laser diodes in the T/R modules. The modulated polarized light is carried in polarization maintaining fibers to the remotely located optical control system. Graded index fiber lenses are used to create collimated light beams at the outputs of the fibers. These N X M light beams are imaged onto EOS2 using lenses S3 and S4. EOS2, like EOS1, determines if light should be directed into Ch1 or Ch2. Using PBS2, a corner prism, NLC SLM2, and PBS3, light beams carrying the received microwave signals are directed into the same time delay units that were used in the transmit mode. After propagation through these delay units, all the relative time delays across the multiple optical beams are cancelled out, resulting in all the light beams emerging from PBSN at the same instant. This plane wavefront formed by the collimated multiple beams at the exit of PBSN are s-polarized when using Ch1 and p-polarized when using Ch2. In order to detect the received signal, the beams have to be deflected by PBS towards the spherical lens S. EOS3 is appropriately turned on or off such that p-polarized light is incident on PBS, whether Ch1 or Ch2 is active. The lens S acts as an optical adder, combining the received signals riding on the N X M optical beams. A photodiode PD adds up the N X M light intensities to generate a photocurrent that represents the microwave radar return (target echo) signal. This signal is fed to a microwave receiver for further processing. Note that NLC SLMR can be programmed to provide an amplitude weighting matrix (desired for lower receive sidelobes) for the N X M received light beams, which when combined with lens S and spatial filter SF can provide noise rejection capabilities. Thus, NLC SLMR provides a capability for adaptive beamforming.

3. SYSTEM DESIGN ISSUES

For a system that requires 1024 independent time delayed channels for 1024 antenna subarrays (or a 1024 antenna element array), the optical system key design features are as follows. Because high power amplifiers are used in the transmit signal chain, it may not be necessary to have 1024 independently driven laser diodes at the input port (near LA1) of the system. Instead, a smaller array (e.g., 5 X 5) could be used, leading to a desired reduction in size and complexity of the microwave splitter network and laser diode drive electronics. It is also possible that the remotely located laser diodes in the T/R modules be used to provide optical power to the NLC system in both the transmit and receive modes. In this case, a large microwave splitter network will be required for the transmit-mode operation.

Each NLC SLM would need 64 X 32 pixels to form the two 32 X 32 (or 1024) pixel arrays coressponding to the two system channels Ch1 and Ch2. Even with a very large 0.5 mm pixel pitch desirable for high interchannel isolation, each 32 X 32 array is a 16 X 16 mm square, implying that the necessary optical component sizes for PBS's, prisms, mirrors, and lenses are commercially available. Because the system is based on polarization switching, optical extinction ratios available from the polarization based components is a critical design parameter. Typical commercial cube PBS's have extinction ratios of >1000:1, with other types such as Thompson-prisms having >100,000 :1 extinction ratios. Note that polarizers labelled P are positioned at certain locations in the optical system where light beams have fixed polarization directions. In this way, unwanted polarizations (or noise) can be reduced. A typical commercial polarizer, such as Polarcor™ with extinction ratios of 10,000:1 can be used for P.

As an example of NLC display technology maturity, Fig.7 shows a 480 X 480 pixel, black and white, twisted nematic, thin-film transistor (TFT) active matrix architecture driven NLC-SLM fabricated at GE-CRD for projector display applications. Three of these monochrome SLMs with red, green, and blue color filters, respectively, are used for making a color projector. All the drive electronics for the designed 4-bit grey-scale SLM control are mounted around the NLC display using GE's High Density Interconnect (HDI) process. The photographs gives an idea of the picture quality and compact assembly of this 4.8 cm X 4.8 cm , 100 μm pitch GE NLC-SLM. The slight color variation across the SLM appears as the SLM is viewed with white light, causing the wavelength dependent NLC birefringence properties to take effect. The NLC cell thickness was 3.8 μm with an SLM frame rate of 120 Hz set by the electronics used. The full-on to full-off response time measured for the NLCs was 15 msec. Note that for the phased-array application, a much smaller number of pixels per NLC SLM will be required, leading to more compact SLM designs with faster frame rates limited by the response times of the NLCs. Using thin cells (< 4 μm) and/or the high voltage transient nematic effect, faster (e.g., 5 msec) response times can be achieved. Recently 100 μsec NLC response times have been demonstrated using the transient nematic effect [13].

4. EXPERIMENTS

Initial experiments are performed to test the on/off ratios available from NLCs. Both the twisted nematic liquid crystals (TNLCs) and birefringent mode NLCs are tested using the set-ups shown in Fig.8. A TNLC cell is set-up between crossed polarizers that are mechanically controlled using a precision motor controlled rotation system by Newport Corporation. A vertically (p) polarized 633 nm 10 mW He-Ne laser beam, after expansion and collimation, normally strikes a 6 μm thick TNLC cell. The cell orientation with respect to the crossed polarizers is carefully adjusted so that maximum light propogates through the TNLC cell with no voltage applied. The light at the output of the analyzer is detected by a photo-diode (UDT Model PIN-HR008) operated in the photovoltaic current mode (no reverse bias). The output of the detector is amplified by a battery operated low noise amplifier (UDT Model 101B) with a dc -16 Hz response and a transimpedance gain of 10^9 V/A, and a input current range of 10^{-13} - 10^{-8} A. The signal output of the amplifier is connected to a dc - 100 KHz HP 3562A dynamic signal spectrum analyzer that measures the light signal in dBVrms. Fig.9 shows the outputs of the spectrum analyzer for the zero volt and 5 Vp @ 50 Ω ,1 KHz conditions. For no voltage applied to the cell, the TNLC molecules rotate the incoming light polarization by 90 degrees, thus allowing the light to pass through the analyzer. The signal detected in this case is 16.69 dBVrms @ dc. When a voltage of around 5 Vp is applied to the cell, the TNLC molecular directors align along the electric field direction, causing essentially no rotation of the incoming polarized light. Thus, a very small light level corresponding to - 55.325 dBVrms @ dc is measured by the spectrum analyzer. The difference between the on and off states measured in the units of dBVrms comes to be 72.02 dBVrms. As dBVrms=20 log[Vrms(max)/Vrms(min)], we get the ratio of the on/off voltage levels to be Vrms(max)/Vrms(min)≈4000. Because current(voltage) generated by an optical detector is proportional to the incident light intensity, the light on/off ratio or contrast ratio available from the TNLC is also 4000:1. This is a 36 dB optical isolation (or 72 dB rf isolation).

The next experiment is performed with a parallel rub birefringent mode NLC cell of 6 μm thickness. Again, the same experimental set-up is used, except, the NLC molecular director is oriented at 45 degrees with respect to the polarizer and analyzer, with this time, using a parallel polarizer/analyzer arrangement. The incoming p-polarized light will provide two equal amplitude, mutually orthogonal optical polarizations, with one component aligned along the molecular director, and another component oriented along the ordinary or n_o axis of the NLC ellipsoid. As a voltage is applied across the cell, the molecules/director rotates, allowing the extraordinary component of the light to see a lower index of refraction than n_e. The other polarization component continues to see the n_o index of refraction. Thus, one component suffers an optical phase shift with respect to the other. The analyzer combines the two components, and the detector measures the constructive and destructive interference patterns. Note that depending on the cell thickness, a certain voltage range can give several maxima and minima in the output interference signal. Fig.10 shows the spectrum analyzer outputs for the maxima (13.3997 dBVrms@ dc) and minima (- 46.365 dBVrms@ dc) achieved with 2.66 Vp and 1.88 Vp @ 50 Ω ,1 KHz conditions. This gives an on/off difference of ≈60 dBVrms which corresponds to a Vrms(max)/Vrms(min)≈1000. Thus the optical isolation or on/off contrast ratio achieved with the parallel rub NLC cell is around 1000:1 or 30 dB (or 60 dB rf isolation). It is expected that by using higher extinction ratio polarizers, higher on/off ratios can be achieved that are only limited by the quality of the NLC cells, where quality is mainly determined by the uniformity of the molecular directors across the cell. Recently, for the phased array optical delay line serial architecture, a 20 to 25 dB optical on/off ratio has been calculated to be adequate for high signal-to-noise radar applications [5].

5. COMPARATIVE STUDIES

When compared to other optical techniques for reversible time delay beamforming [1-6], the proposed optical system offers the following features listed in Table.1.

Table 1.

Feature	*Advantage*	*Benefit*
System uses the mature, low-cost nematic liquid crystal display technology for making the optical switch arrays	Use of commercially developed and tested components whose large-scale fabrication and testing procedures are well established	Reduces system development costs and overall system cost
Two dimensional (2-D) optical architecture	Inherently higher channel packing density versus integrated-optic (IO) planar systems	Phased-arrays requiring 1,024 independent channels can easily be accomodated in a 3.2 X 1.6 cm processor cross-section
Free-space plane-to-plane optical interconnections using bulk imaging optics	No tedious and complex fiber-switch interface alignment procedures required per switch like in other planar IO systems	Reduced interconnection complexity greatly lowers system assembly costs for a large >1000 element radar; simpler system assembly
High (e.g., 4000:1) optical on-off ratio available from nematic liquid crystals used in making the optical switch	High optical switching isolation is possible (e.g., 36 dB optical or 72 dB rf isolation)	High signal-to-noise ratio per processing channel can be achieved for radar applications
Thousands of planar integrated optical switches replaced by a postage-stamp-size optical all-analog polarization control device and a polarizing beam splitter	High pixel packing density of optical device leads to small size; 1,024-antenna-element N-bit time delay control via N+1 3.2 X 1.6-cm liquid crystal devices	Optical device provides centralized time delay control in one chip/bit—easy to replace and repair
System has potentially low optical insertion loss, e.g., -3.0 dB for a 10-bit delay line	System input-output rf-to-rf insertion loss can be minimized as system optical losses are small due to low loss components and efficient free-space coupling optics	Can use lower power lasers and/or lower efficiency detectors with better noise characteristics
Large area nematic liquid crystal display processing technology (e.g., 10 inch diagonal commercial nematic liquid crystal displays for video)	Liquid crystal pixel pitch can be large, e.g., 0.5 mm. Pixel size and positioning can be easily controlled via the 2-D fabrication process	Increased channel isolation and lower inter-channel crosstalk gives higher output signal-to-noise ratio
Optical architecture design allows the use of polarization filtering	High extinction ratio (e.g., 10,000:1) polarizers can be placed at different positions in the channels to reduce noise	Higher channel fidelity- rf output signal-to-noise ratio

Optical architecture design allows the use of spatial filtering	Spherical lenses used for free-space imaging provide the Fourier planes for spatial filtering to reduce noise	Spatial noise from unwanted diffraction effects, dust particles, etc, can be removed to improve channel fidelity
No large (e.g., 1024:1) microwave combiner network required on receive (unlike planar IO systems)	A single spherical lens acts as an optical combiner, adding the N (e.g., 1024) channels in space	Reduction in EMI and insertion losses on receive to provide system with higher sensitivity
N (e.g., 1024) received optical beams can easily be programmed with 10-bit amplitude weighting before optical summation/distribution	A liquid crystal array can apply amplitude weights to the N received (and transmit) signals to generate a desired receive (and transmit) beam radiation pattern	On receive (and transmit), low side-lobe levels for the radar can be achieved resulting in higher target discrimination ability
Beamformer and antenna remotely connected via two multifiber links associated with the transmit and receive signals	Centrally located beamformer is easily accessible for monitoring and repair	High EMI at antenna array does not affect remote beamformer; Reduced antenna array weight via smaller-sized antenna backpaneling
Dual channel system for time multiplexed antenna beam scanning	The slow response of the nematic liquid crystals is overcome for radar beam scanning using a two channel scanning approach	e.g., Upto 200 beams/s fast scan rates can be provided with 5 ms response nematic liquid crystals (e.g., using the transient nematic effect)
Free-space optical delays are used for delays, e.g., < 6 ns, or the least significant bits of the delay line. (The free-space delays can have folded paths)	Free-space delay lines do not require fiber coupling optics like those used in all the delays in the planar fiber-based IO systems	The 2-D optical architecture allows the use of 2-D free-space delay lines that reduces system complexity and lowers insertion losses

6. CONCLUSION

Because of the maturity of present-day NLC commercial display technology in terms of ease of fabrication, performance, and low cost, and the nature of the time delay-based phased-array application that requires 1000's of optical switches that require high isolation, and low insertion loss, it may be possible for the proposed two dimensional, free-space optical interconnect-based optical system to provide the much desired system solution for the advanced wideband phased array radar application. This optical system can be used for high resolution large ground-based radars, large ship-board radars, and wide bandwidth airborne radars. Future work involves system analysis, design, and further experimental studies. The basic NLC-based time delay concept can be extended to an integrated unit, bulk optics-based design using GRIN lens-fiber delay loops, as shown in Fig.11. Using a 2 X 2 cm beam splitter, greater than ten, 10-bit time delay channels can be formed. These and other extensions of NLC-based time delay control will be studied and demonstrated in future research.

7. ACKNOWLEDGEMENTS

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GE THREE DIMENSIONAL OPTICAL TIME DELAY CONTROLLER

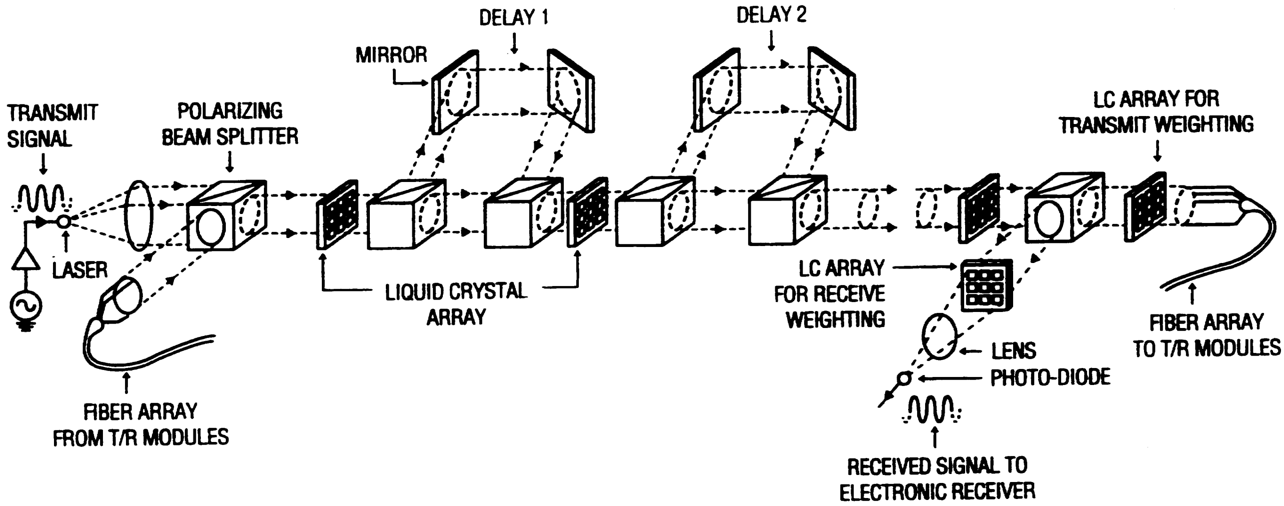


Fig.1 A typical 3-D view of the proposed optical time delay controller.

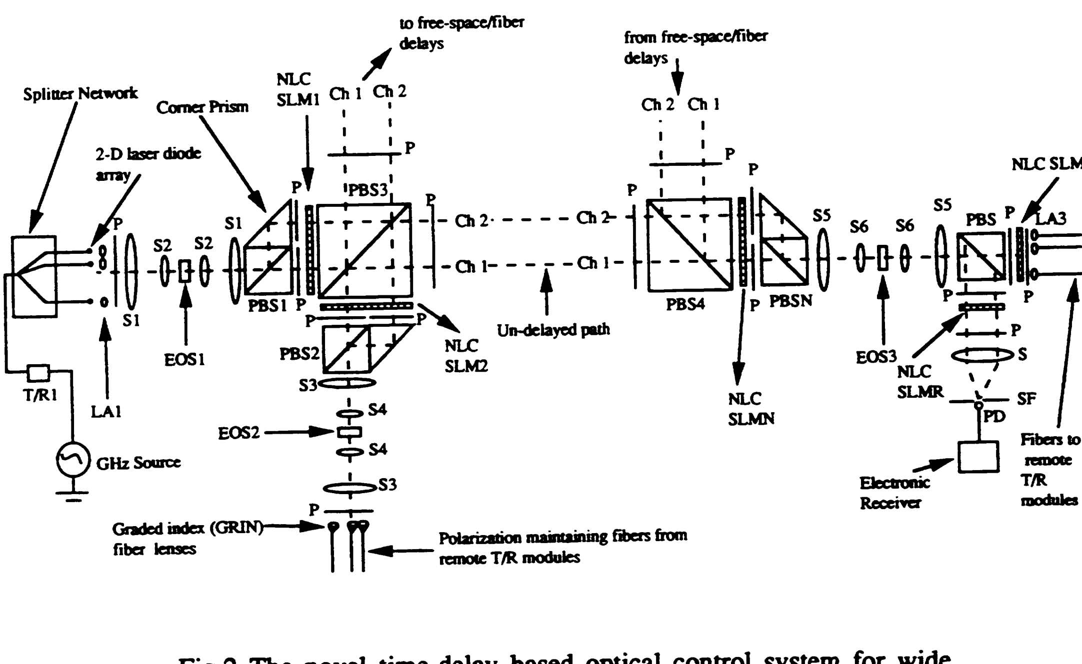


Fig.2 The novel time-delay based optical control system for wide instantaneous bandwidth phased array antennas (top view).

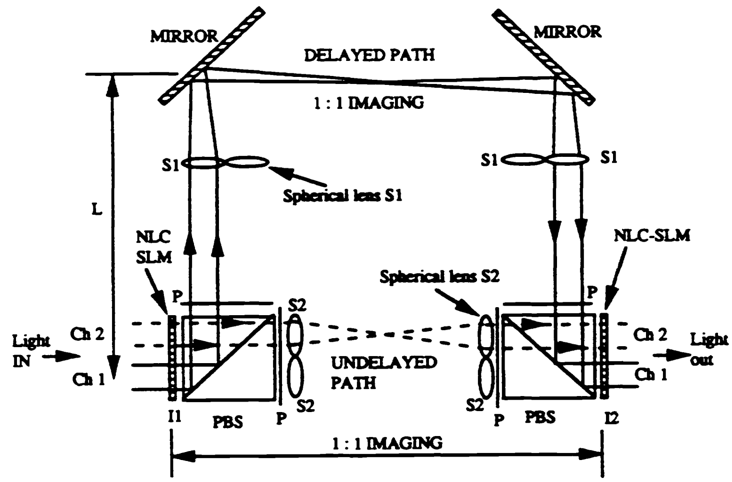


Fig.3 A free-space time delay unit (top view).

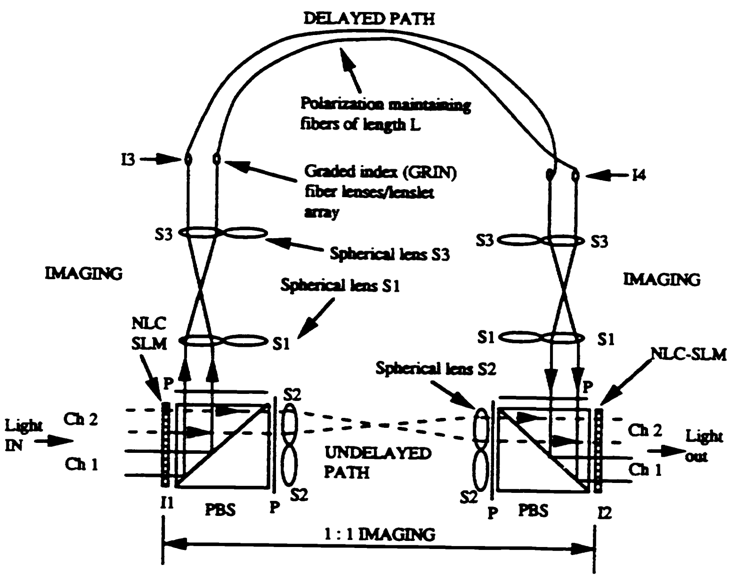


Fig.4 A fiber-based time delay unit (top view).

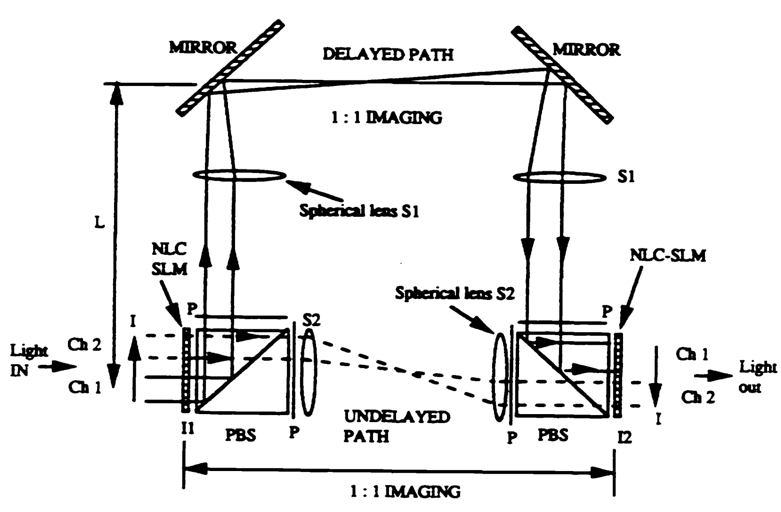


Fig.5 A free-space time delay unit using single spherical imaging lenses (top view).

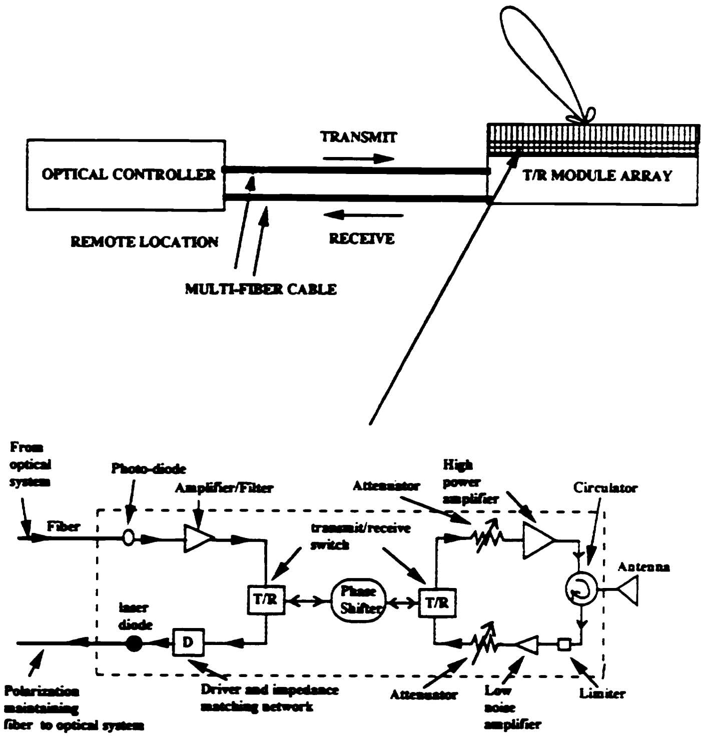


Fig.6 A typical system scenario and the remote T/R module for the system.

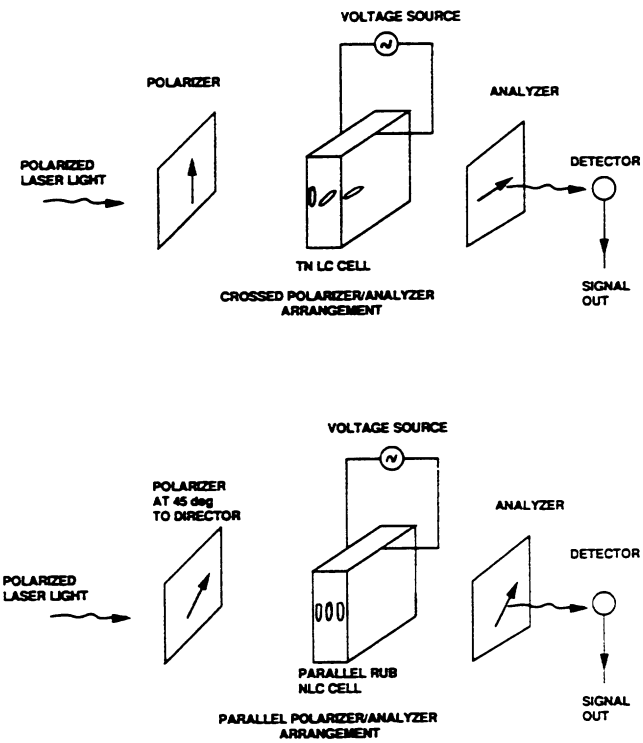


Fig.8 Experimental set-up to test the contrast (on/off) ratios possible from twisted nematic liquid crystals (TNLC) and parallel rub birefringent mode nematic liquid crystal cells.

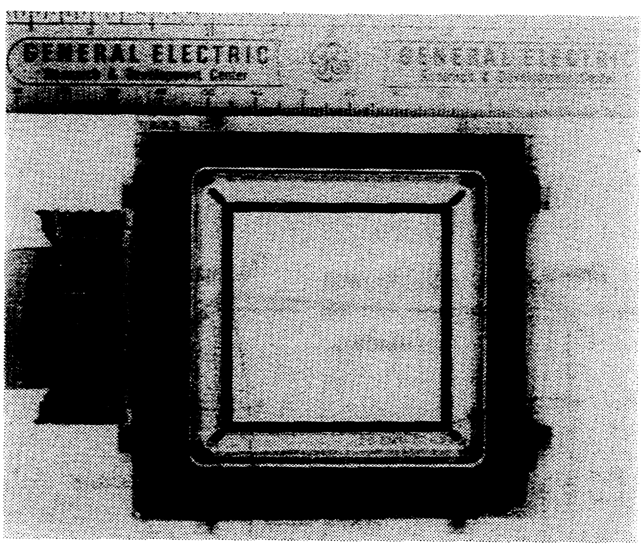
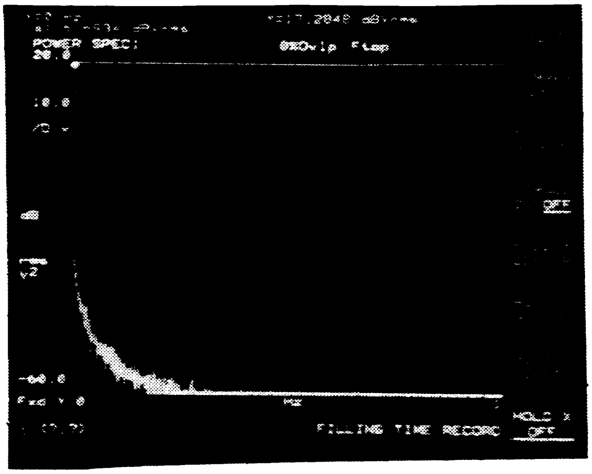


Fig.7 Photographs showing the 480 X 480 pixel, 4.8 cm X 4.8 cm, monochrome, 4-bit grey-scale, twisted nematic, thin-film transistor (TFT) active matrix architecture driven NLC-SLM fabricated at GE-CRD for projector display applications.



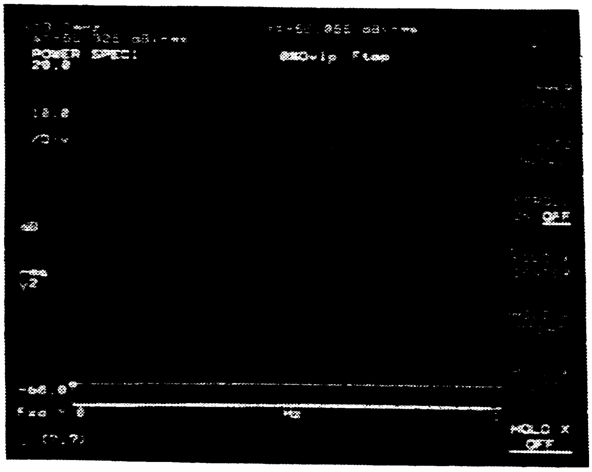


Fig.9 Spectrum analyzer traces from the TNLC cell showing 16.69 dBVrms (on-state) and -55.325 dBVrms (off-state) @ dc voltage levels. This corresponds to a Vrms(max)/Vrms(min)=optical contrast ratio ≈ 4000, giving a 36 dB optical isolation (or 72 dB rf isolation)

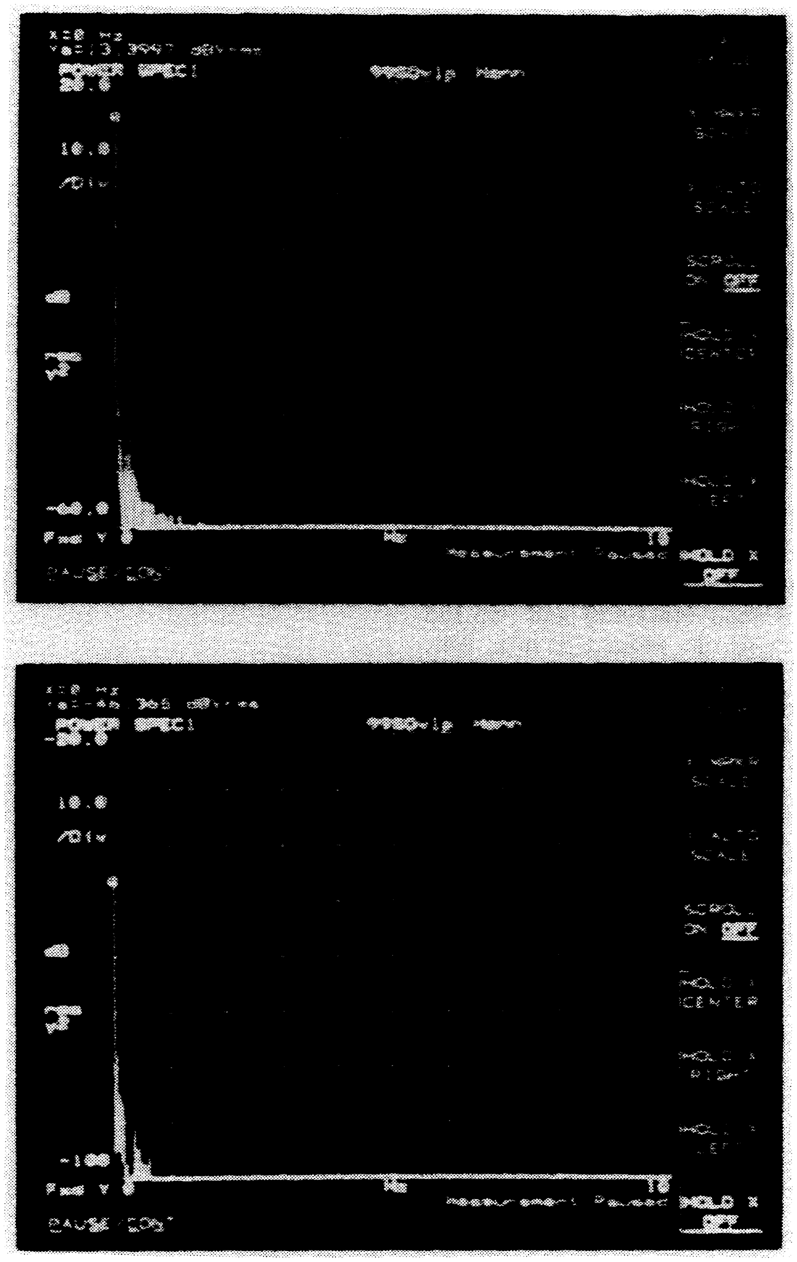
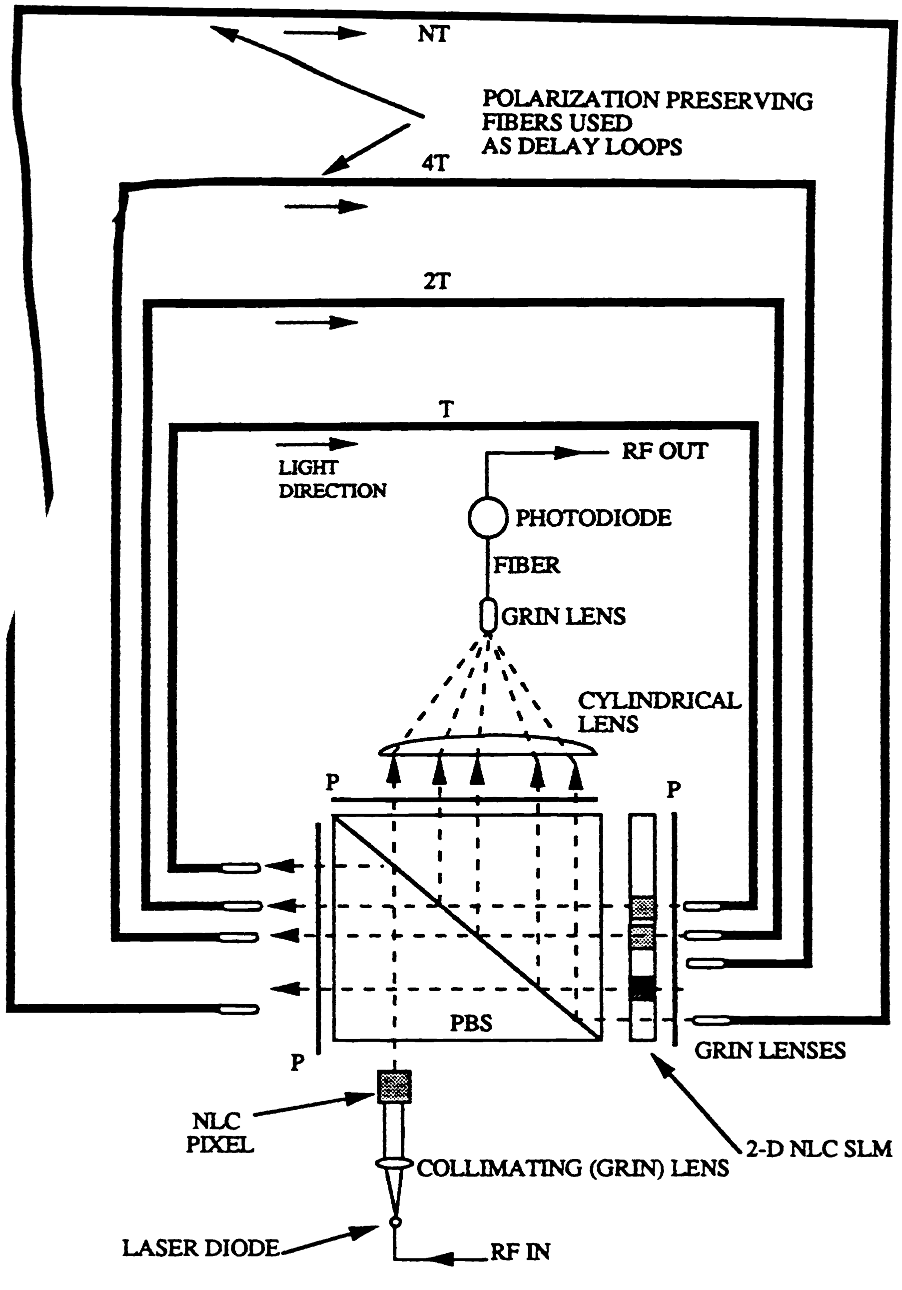


Fig.10 Spectrum analyzer traces from the parallel rub NLC cell showing 13.3997 dBVrms (on-state) and -46.365 dBVrms (off-state) @ dc voltage levels. This corresponds to a Vrms(max)/Vrms(min)=optical contrast ratio ≈ 1000, giving a 30 dB optical isolation (or 60 dB rf isolation)



TOP VIEW SHOWS A SINGLE N-BIT FIBER-OPTIC DELAY LINE; OTHER N-BIT DELAY LINES ARE PRESENT UNDER THE TOP LAYER.

Fig.11 shows an integrated time delay unit formed with a bulk optic polarizing beam splitter and GRIN lens-fiber delay loops. Using a 2 X 2 cm beam splitter, greater than ten, 10-bit time delay channels can be formed with 10 rf in and rf out ports.